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THERMO-ELASTIC-PLASTIC STRESSES IN MULTI-LAYERED CYLINDERS

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One of the many efforts undertaken to increase the life of gun tubes and/or increase their resistance to erosion involves the use of liners fabricated from different materials. A finite difference computer code for investigating the thermo-elastic-plastic response of gun tubes has been expanded to include multi-layered cylinder response to time dependent boundary conditions. Considered are both cyclic heat input and cyclic stress input. Response
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20. ABSTRACT (Cont'd)

curves from inputs representative of repeated firing cycles are presented. The emphasis in this report is on the transient temperature response and on the thermo-elastic stresses and mechanical stresses in the layers.

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INTRODUCTION

One of the many efforts undertaken to increase the life of gun tubes and/or increase their erosion resistance involves the use of liners fabricated from materials differing from the base material of the gun tube. Typical properties sought in these materials, many of which are refractory materials or alloys of them, are high melting points for protection against erosion due to the high flame temperatures, different elastic moduli to effect transmission of loads to the base gun tube, etc. Currently most designs are of the two-layer system or liner-jacket type and with a variation that the liner may be coated or not. This report does not consider coatings for reasons to be mentioned later.

In this report, the response of monobloc and multi-layered large caliber gun tubes due to a typical firing schedule is calculated. This response is found using a finite difference computer code reported in references 1 and 2 for transient temperatures and thermo-elastic-plastic stresses. The program was updated to accept time dependent boundary conditions and to apply to multiple layers. A consistent set of data for a firing pulse was found in reference 3 for a specific weapon and this configuration was chosen for this study.

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[1]Vasilakis, J. D., "Temperatures and Stresses Due to Quenching of Hollow Cylinders," Transactions of the Twenty-Fourth Conference of Army Mathematicians, ARO Report 79-1.
[2]Vasilakis, J. D. and Chen, P. C. T., "Thermo-Elastic-Plastic Stresses in Hollow Cylinders Due to Quenching," Transactions of the Twenty-Fifth Conference of Army Mathematicians, ARO Report 80-1.
[3]Kovacs, J. E., "Computer Methodology For Large Caliber Artillery Cannon Heating and Cooling," Technical Report ARSED-TR-80001, December 1980.

The computer program is a two part program. Knowing gas temperatures and heat transfer coefficients as a function of time during the firing cycle allows the computation of the transient temperatures in the gun tube. This is accomplished in the first part of the program. These temperatures are then used in the second part to calculate the associated thermo-elastic stresses. The program is capable of computing the thermal response of the tube for any desired firing cycle, thus monitoring an average temperature use at the bore. This can be used in cook-off studies, cook-off being the undesirable condition of premature propellant ignition. The temperatures at any time are saved on disk and are used as input to the stress portion of the program. The interest here is in the mechanical and thermal stresses due to the pressure pulse and the thermal pulse respectively. It should be mentioned that the thermal problem and stress problem are treated as uncoupled.

DESCRIPTION OF THE PROBLEM

The partial differential equation for determining the temperature in a cylinder is given by

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rk^L(T)\frac{\partial T}{\partial r}\right) = \rho^L(T)c^L(T)\frac{\partial T}{\partial t} \qquad (1)$$

where the superscript L refers to the layer number and

T is temperature,

$k^L(T)$ is thermal conductivity in layer L,

$\rho^L(T)$ is density in layer L,

$c^L(T)$ is specific heat in layer L,

r is radial distance

and t is time. The problem is assumed to be axisymmetric and axial effects are ignored. Figure 1 shows a typical geometry. At the interface between layers, the following continuity conditions must apply:

continuity of temperature

$$T^L \Big|_{r_L^-} = T^{L+1} \Big|_{r_L^+} \tag{2}$$

and continuity of heat flux

$$k^L(T) \left.\frac{\partial T}{\partial r}\right|_{r_L^-} = k^{L+1}(T) \left.\frac{\partial T}{\partial r}\right|_{r_L^+} \tag{3}$$

where r_L is the radius to the outer surface of the L^{th} layer. Contact resistance between layers is ignored at this time.

The above quantities are dimensionless, normalized to the properties of the steel layer.* Thus if the thermal conductivity can be written as

$$\bar{k}^L(T) = k^{SL}{}_{So} k^L(T) \tag{4}$$

where $\bar{k}^L(T)$ is the dimensioned thermal conductivity of the L^{th} layer and $k^{SL}{}_{So}$ is the thermal conductivity of the steel layer at some reference temperature, then for L = 1

$$\frac{k^1(T)}{k^{SL}{}_{So}} = k^1(T) \tag{5}$$

and L > 1,

$$\frac{\bar{k}^L(T)}{k^{SL}{}_{So}} = \frac{k^L{}_o}{k^{SL}{}_{So}} kL(T) \tag{6}$$

*In the results that follow, one of the layers was steel. Other definitions or material properties can be used so long as one is consistent.

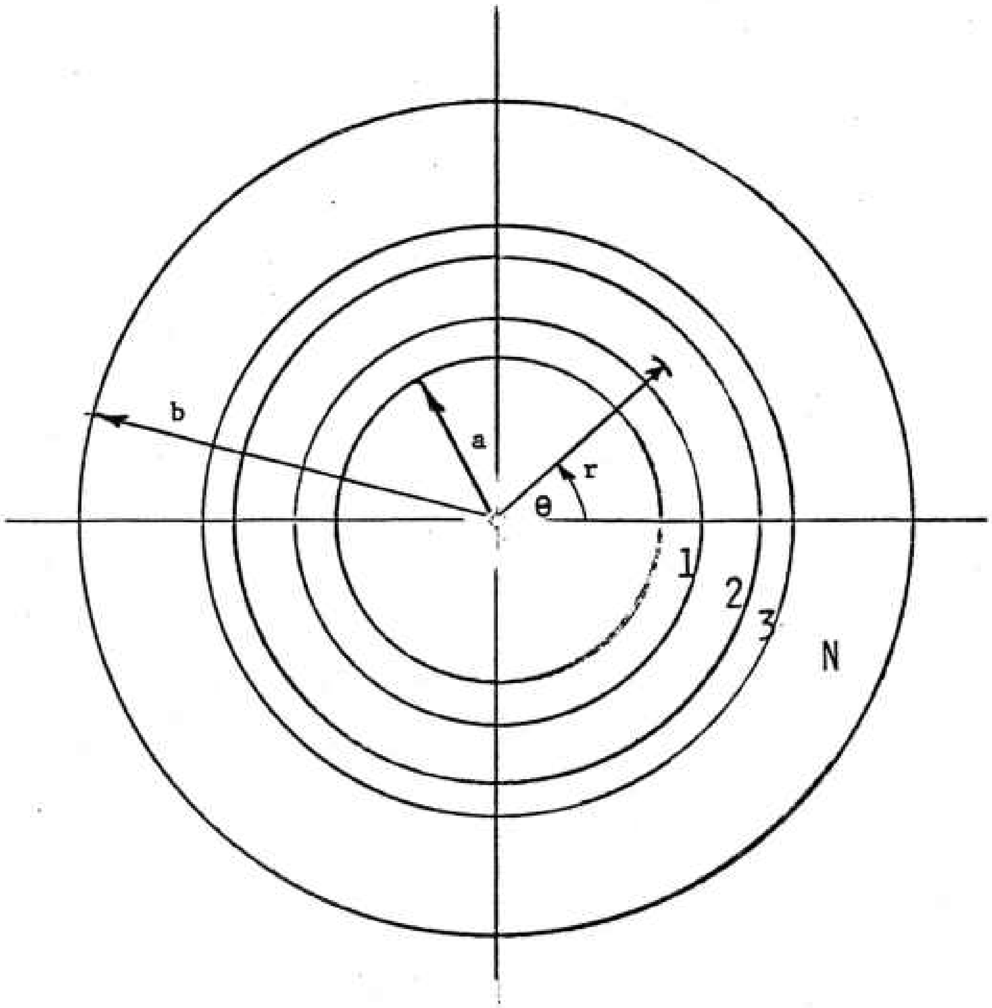

FIGURE 1. TYPICAL MULTI-LAYERED GEOMETRY

The specific heat and density are defined in similar fashion. Also

$$\bar{r} = \frac{r}{b} \quad , \quad \bar{T} = \frac{T}{T_{gas}} \tag{7}$$

where T_{gas} is initial gas temperature, and time

$$\tau = \frac{k^{SL}{}_{So}\,t}{\rho^{SL}{}_{o}\,c^{SL}{}_{o}\,b^2} \tag{8}$$

The stresses are computed in the second part of the program. Again, finite differences are used. The equations of compatibility and equilibrium are written at each node,

$$\frac{\partial \sigma_r}{\partial r} + \frac{1}{r}\left(\sigma^L{}_r - \sigma^L{}_\theta\right) = 0 \tag{9}$$

$$\frac{\partial \varepsilon_\theta{}^L}{\partial r} + \frac{1}{r}\left(\varepsilon^L{}_\theta - \varepsilon^L{}_r\right) = 0 \tag{10}$$

where L identifies the layer. Between layers, the continuity conditions for radial stress and radial displacement must be satisfied. Between the L and L+1 layer, therefore,

$$\sigma^L{}_r = \sigma^{L+1}{}_r \quad \text{and} \quad u^L = u^{L+1} \tag{11}$$

Initial stresses may exist due to fabrication methods used for the multi-layered cylinder. The Prandtl-Reuss equations are used to relate the incremental stress and strain. The assumption of plane strain is used. The equations (9) and (10) are written in finite difference form. Expressions relating incremental stress to incremental strain similar to those of Yamada, et al[4] but including the effect of temperature are used to express equation

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[4]Yamada, Y., Yoshimura, N., and Sakuri, T., "Plastic Stress-Strain Matrix and Its Application For the Solution of Elastic-Plastic Problems by the Finite Element," International Journal of Mechanical Sciences, 1968, V 10, pp. 343-354.

(9) in terms of the incremental strains.

For the computation of the thermal stresses, the new temperature distribution and temperature increments are used at each time step. As the yield criterion is approached, the temperature increments are themselves divided into smaller increments to maintain smaller load steps.

BOUNDARY CONDITIONS

It is important when solving for the response due to firing pulses of these geometries to have a set of consistent boundary conditions. For the thermal response, either the temperature versus time on the boundaries or the gas temperature and heat transfer coefficients are required and for the pressure pulse, the bore pressure versus time. Kovacs[3] considered the transient temperature response for several firing cycles, see Figure 2, and did give in his report a complete set of data. The data is based on a program relying on empirical information for heat flux and applied to a large caliber weapon with chrome plating. It was felt that the heat transfer coefficients generated would apply to a steel monobloc tube or to a multi-layered tube where the steel layer was at the bore. Lacking better input, however, the data was used in all cases.

Future plans include the incorporation of an initial program for the purpose of analytically computing the heat transfer coefficients for the designated multi-layer properties. The problems encountered in comparing responses of different multi-layered designs would then be alleviated.

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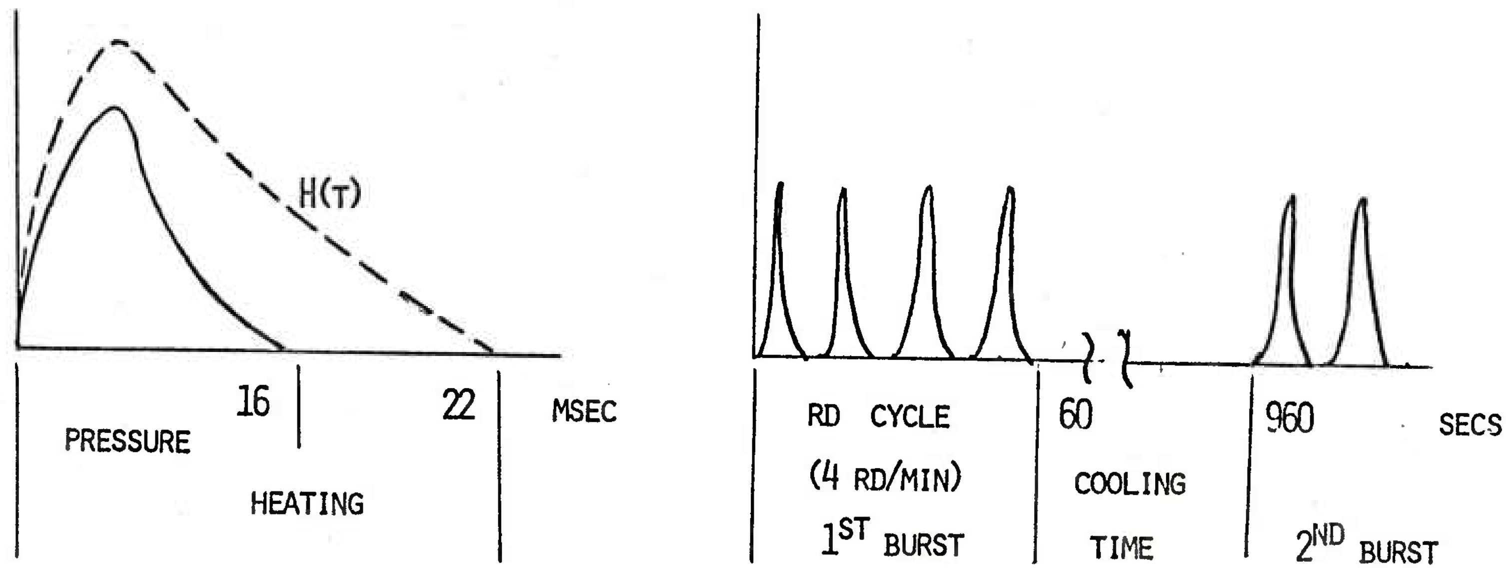
[3]Kovacs, J. E., "Computer Methodology For Large Caliber Artillery Cannon Heating and Cooling," Technical Report ARSED-TR-80001, December 1980.



(a) (b)

FIGURE 2. HEATING AND PRESSURE PULSES (AFTER REF. (3))

RESULTS

Several runs have been made, mainly to show the different problems that can be accommodated by the computer program. Once a geometry has been chosen, either monobloc or multi-layer, and the material properties found, the first part of the program can be run for temperature response versus time. One can look at both the temperature distribution throughout the tube wall and the change in bore temperature in time. If a firing cycle consists of a number of firing pulses and pauses, the bore temperature can be monitored in time. If stresses are required, the temperature distributions at each time step are saved in a file which is subsequently used as input to the second part of the computer program. These temperature distributions are used to compute the thermal stresses. The associated stress pulse can also be applied to the tube, either by itself for a mechanical response or with the thermal loads for a combined response. As mentioned before, however, the thermo-mechanical problem is considered to be uncoupled. If the distortion energy criterion is satisfied, then an incremental thermo-elastic-plastic analysis will be performed. It should be noted that while some examples showing elastic-plastic response are presented, the loading generated from the data of reference 3 was not of sufficient magnitude to cause this and the stress pulse was increased to cause the program to perform a plasticity solution. If the problem is more realistically modeled with material properties and yield strength a function of temperature, it may not be necessary to artificially induce this type of solution.

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[3] Kovacs, J. E., "Computer Methodology For Large Caliber Artillery Cannon Heating and Cooling," Technical Report ARSED-TR-80001, December 1980.

Figure 3 shows the result of the problem of thermal response due to the heat pulse for a monobloc tube. The response to a single pulse is shown for different time increments. An important function of this type of analysis is to be able to predict bore temperatures under various firing cycles and for long firing periods. Being able to use coarser time increments allows the prediction of bore temperatures for longer periods. Figure 4 shows the response of a monobloc tube for about five cycles.

Table I shows the properties for the multi-layered geometry chosen. The liner is a tantalum tungsten alloy (Ta-10W) with a steel jacket. The bore diameter is 3.351 inches, the outside diameter is 5.6 inches, and the interface diameter is 4.1 inches. The properties are assumed constant in temperature but a variation in temperature is allowed. Figures 5 and 6 are equivalent to Figures 3 and 4 for a multi-layered tube. Figures 7 and 8 show the stress response of a monobloc tube to a stress pulse and a thermal pulse, respectively. It should be noted that most of these results show the effect at the bore. During the early stages of the response, there is little effect on the rest of the tube.

Figure 9 shows the stress response of a multi-layered cylinder (Ta-10W/ Steel). The material behavior is assumed to be elastic. The change in the tangential stress at the bore with time is shown for the stress pulse (M curve) and for the temperature distributions (T curve). The combined curve shows the computed stresses due to both the thermal and mechanical loading. Since only elastic behavior occurs, however, the same combined loading curve could be arrived at by assuming the results for the individual loads.

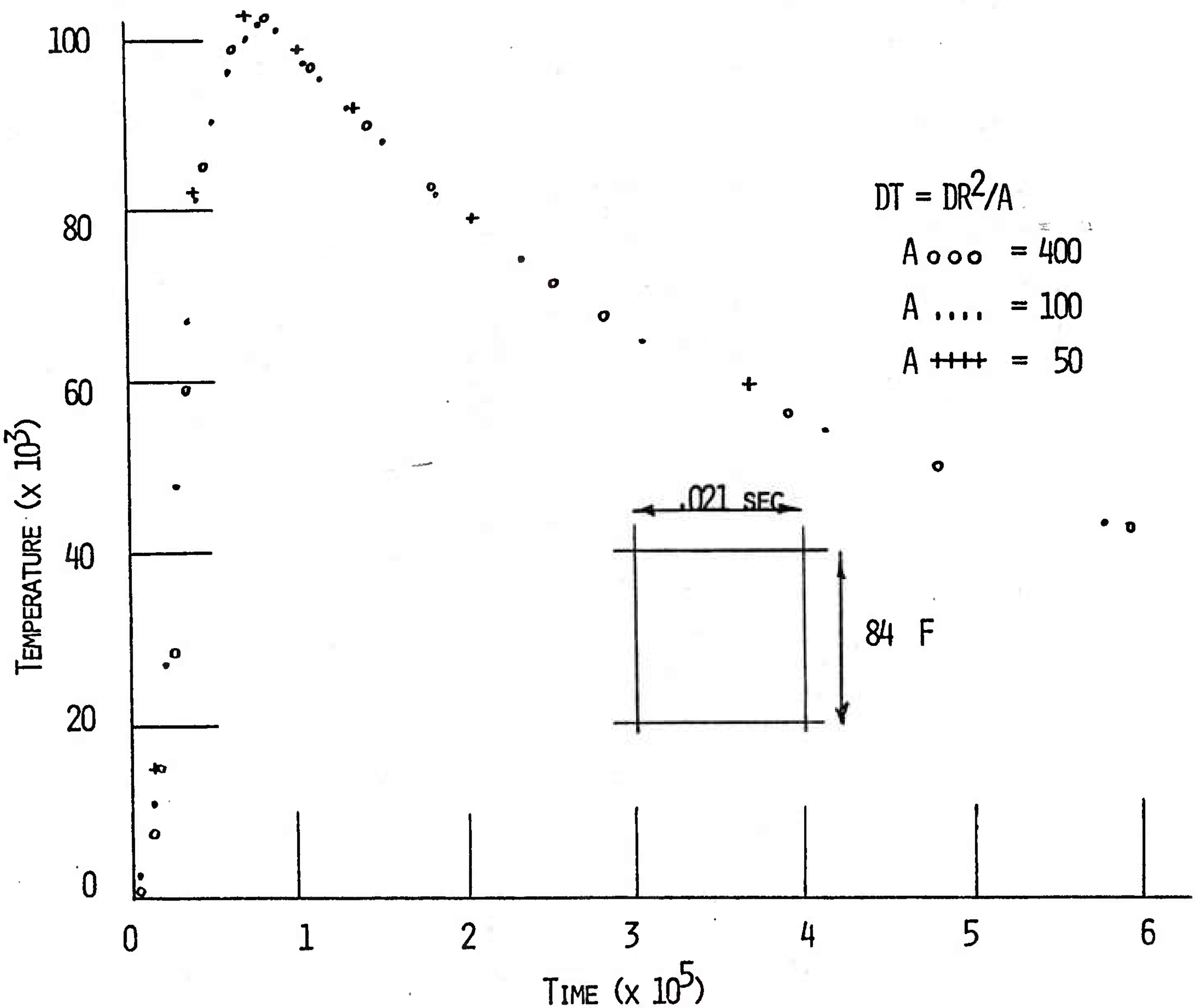

Figure 3. Effect of Time Increment on Pulse Shape. Monobloc Tube.

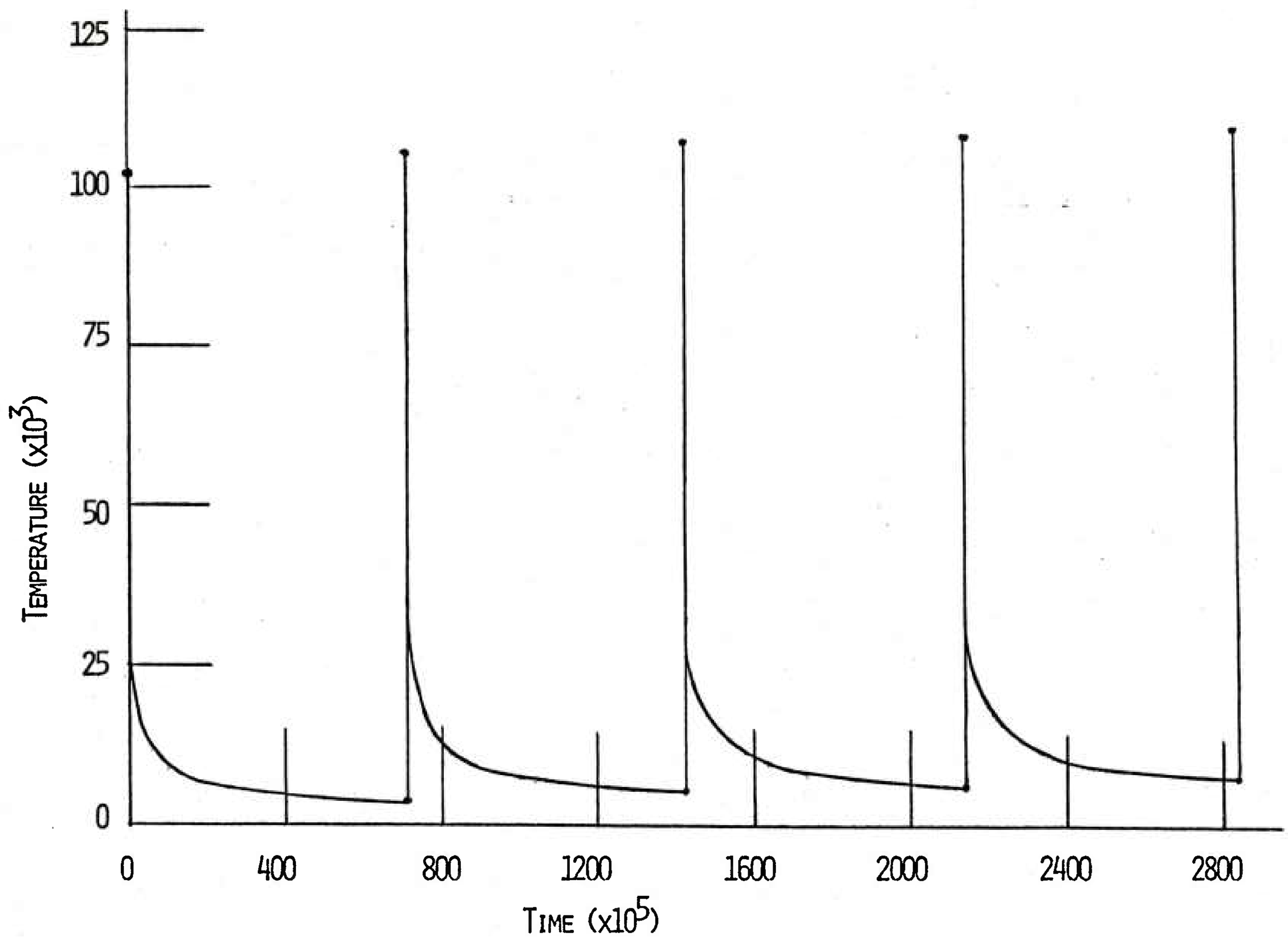

FIGURE 4. BORE TEMPERATURE CHANGE UNDER REPEATED FIRING, MONOBLOC TUBE.

TABLE I. MATERIAL PROPERTIES OF MULTI-LAYERED CYLINDER
LINER: TA-10W
JACKET: STEEL

Radius			Properties (Room Temp)					
	Inch			Liner		Jacket		
Inside	3.351	.6	K	.0012	2.65	.000453	1	BTU/sec°F in
Interface	4.101	.732	C	.0339	.317	.107	1	BTU/#°F
Outside	5.6	1.0	ρ	.607	2.14	.284	1	$\#/in^3$

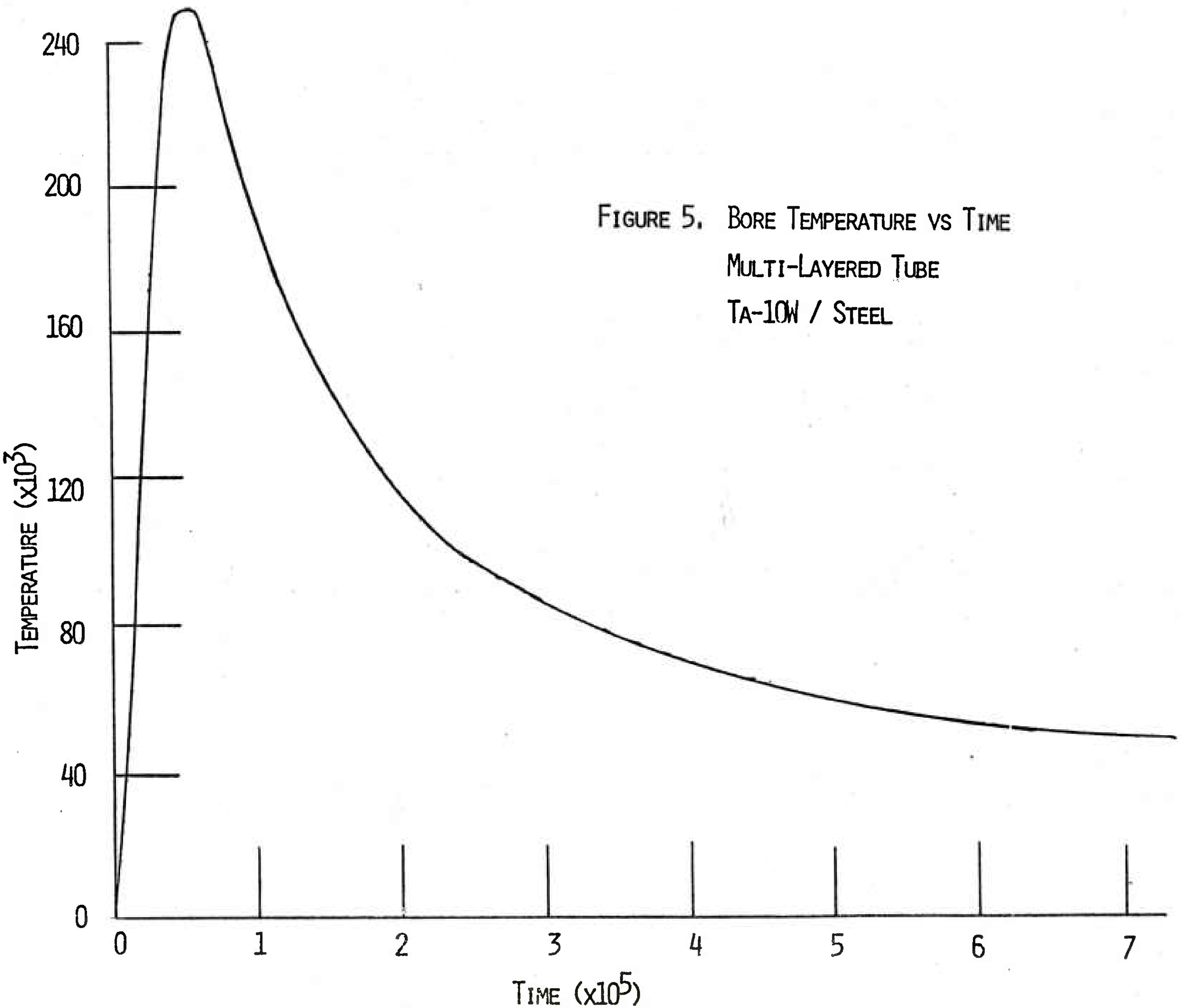

Figure 5. Bore Temperature vs Time
Multi-Layered Tube
Ta-10W / Steel

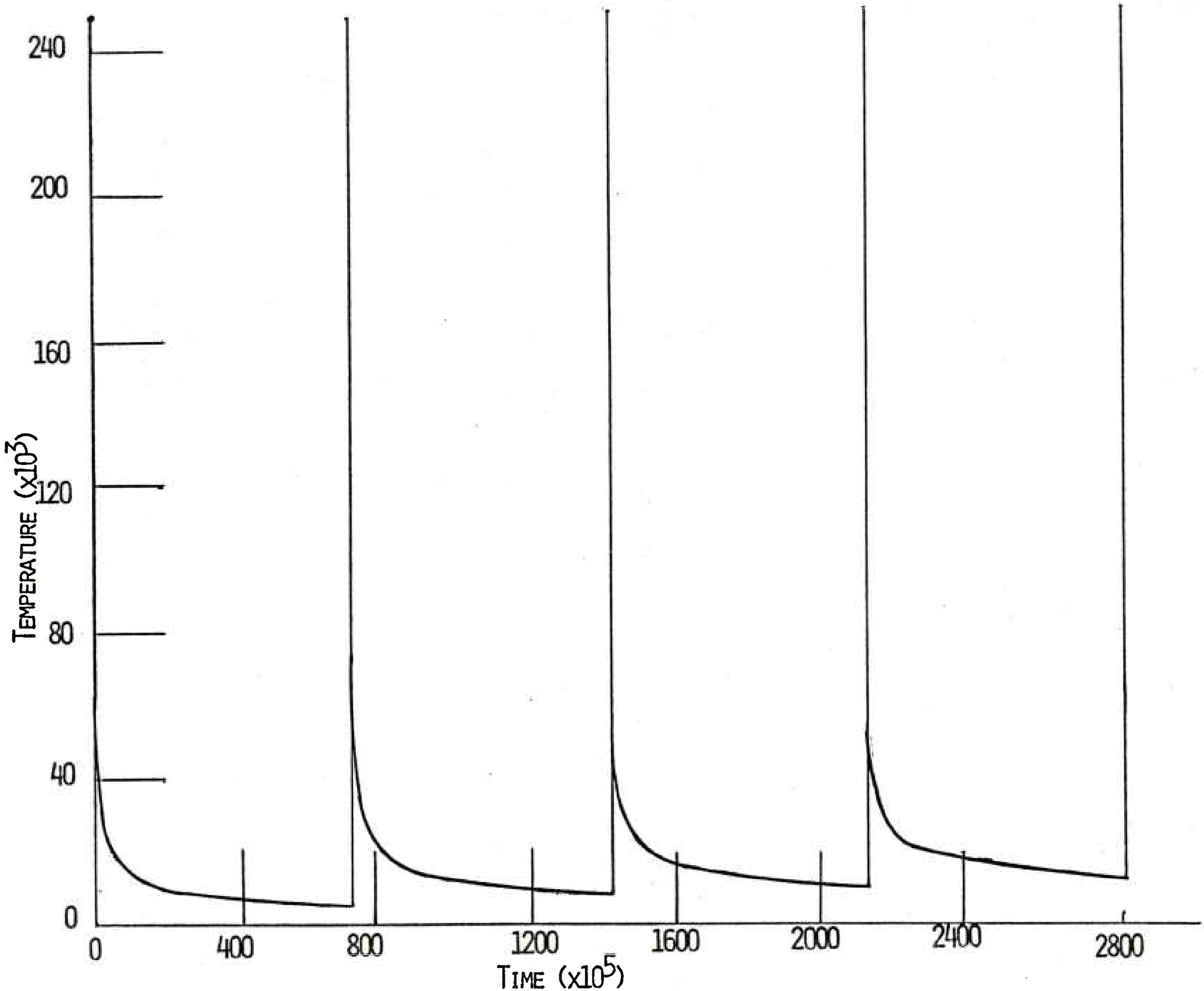

FIGURE 6. BORE TEMPERATURE VS TIME (5 CYCLES). TA-10W / STEEL

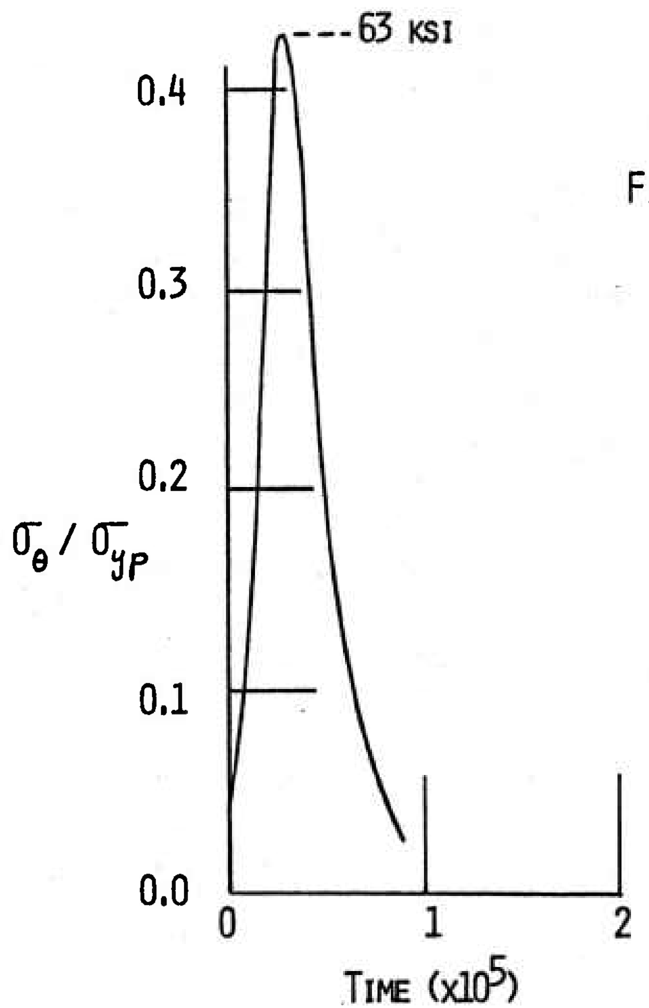

FIGURE 7. RESPONSE OF MONOBLOC TUBE (BORE STRESS) TO A GIVEN STRESS PULSE.

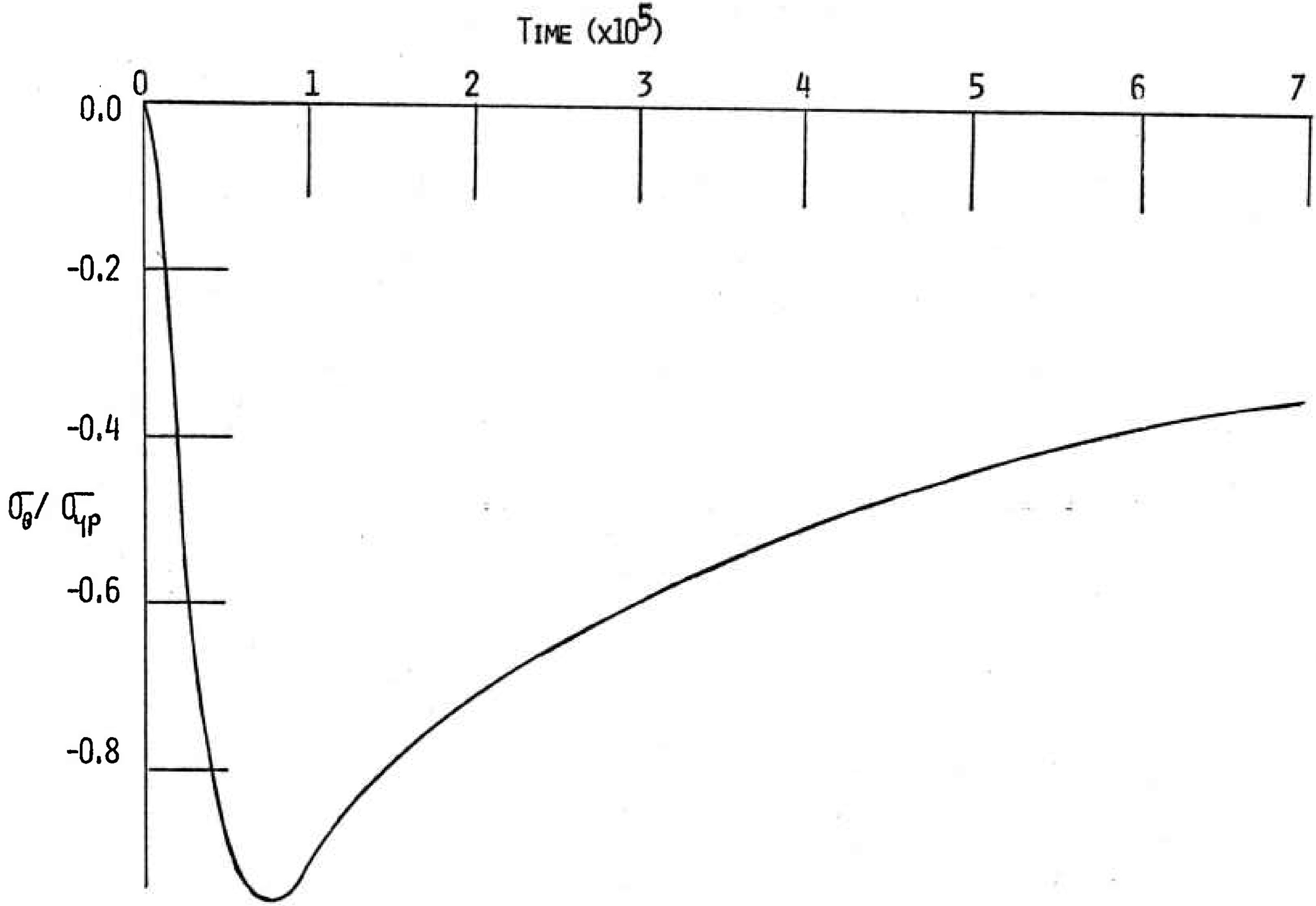

FIGURE 8. THERMAL STRESSES DUE TO SINGLE FIRING PULSE.
(MONOBLOC TUBE)

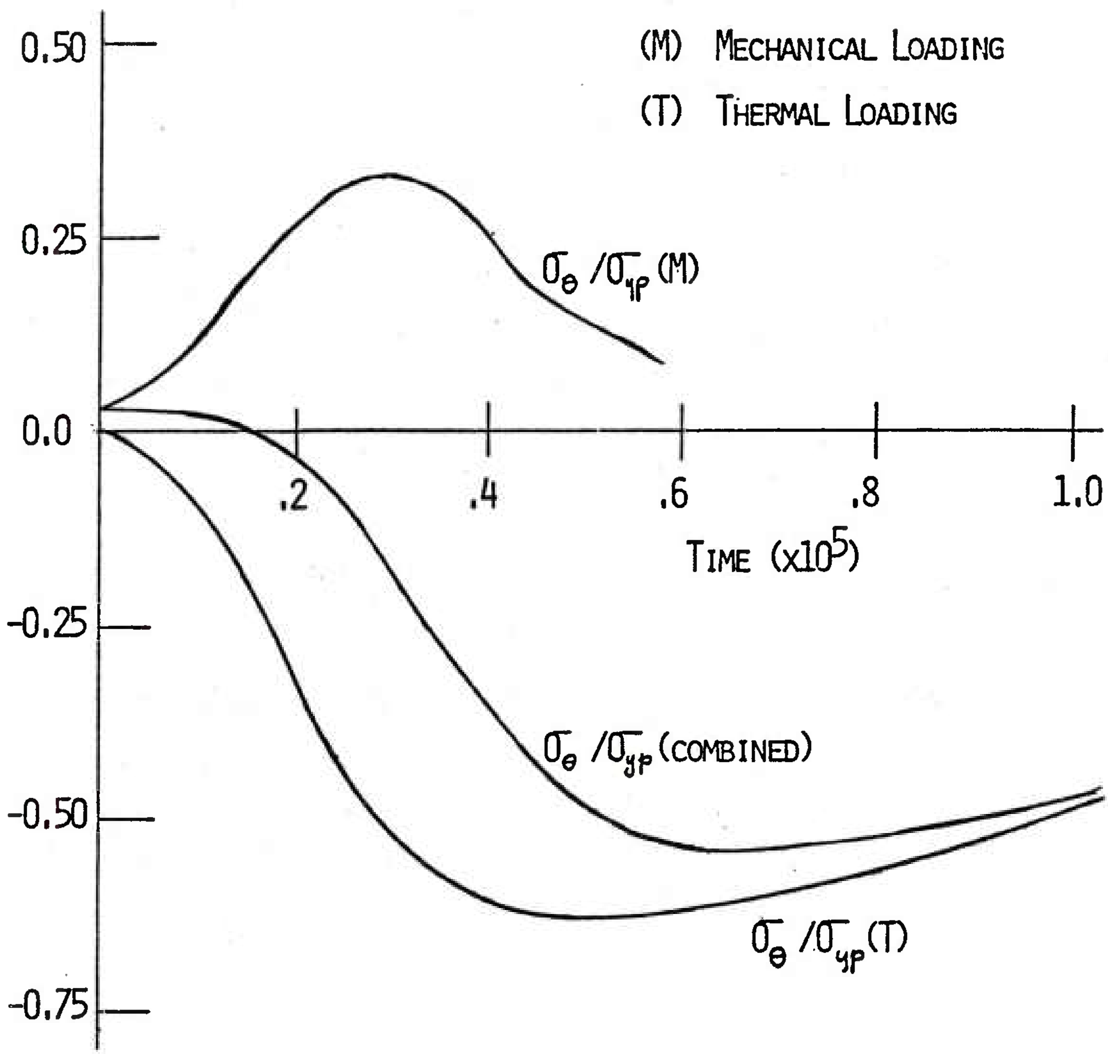

Figure 9. Bore Stress vs Time.
Elastic Response, Multilayered Cylinder

An elastic-plastic response due to the applied pressure pulse is shown in Figure 10. The curve labeled pressure is actually the radial stress at the bore, σ_r, and the pressure should be $|\sigma_r|$. The other three curves are the response of a monobloc steel tube and two multi-layered systems, a Ta-10W liner with a steel jacket and a steel liner with a Ta-10W jacket. The figure shows mainly the effect of the elastic modulus of the materials. The Ta-10W liner, having a modulus approximately one third less than steel, transmits the load towards the interior of the tube better than the other configuration which has a more rigid liner. Figure 11 was included just to show that the stresses throughout the wall thickness are computed. The figure shows the response of a Ta-10W liner/steel jacket cylinder to combined thermo-mechanical loads.

Figure 12 shows the elastic response due to thermo-mechanical loads in a multi-layered cylinder with a steel liner and Ta-10W jacket. Figure 13 shows the thermo-elastic-plastic response for the same configuration. The radial stress and the tangential stress at the bore are shown as the change in time.

CONCLUSIONS

The above results are an indication of the type of problems to which the computer program can be applied. Several layers can be handled and for the two-layer geometry, initial stresses due to interference fits (for fabrication reasons) can be calculated. In either program part, the properties can be considered as a function of temperature. While the program does not have the full responsibility of a general purpose finite element program, for the allowed geometry, a wide variety of behavior can be examined.

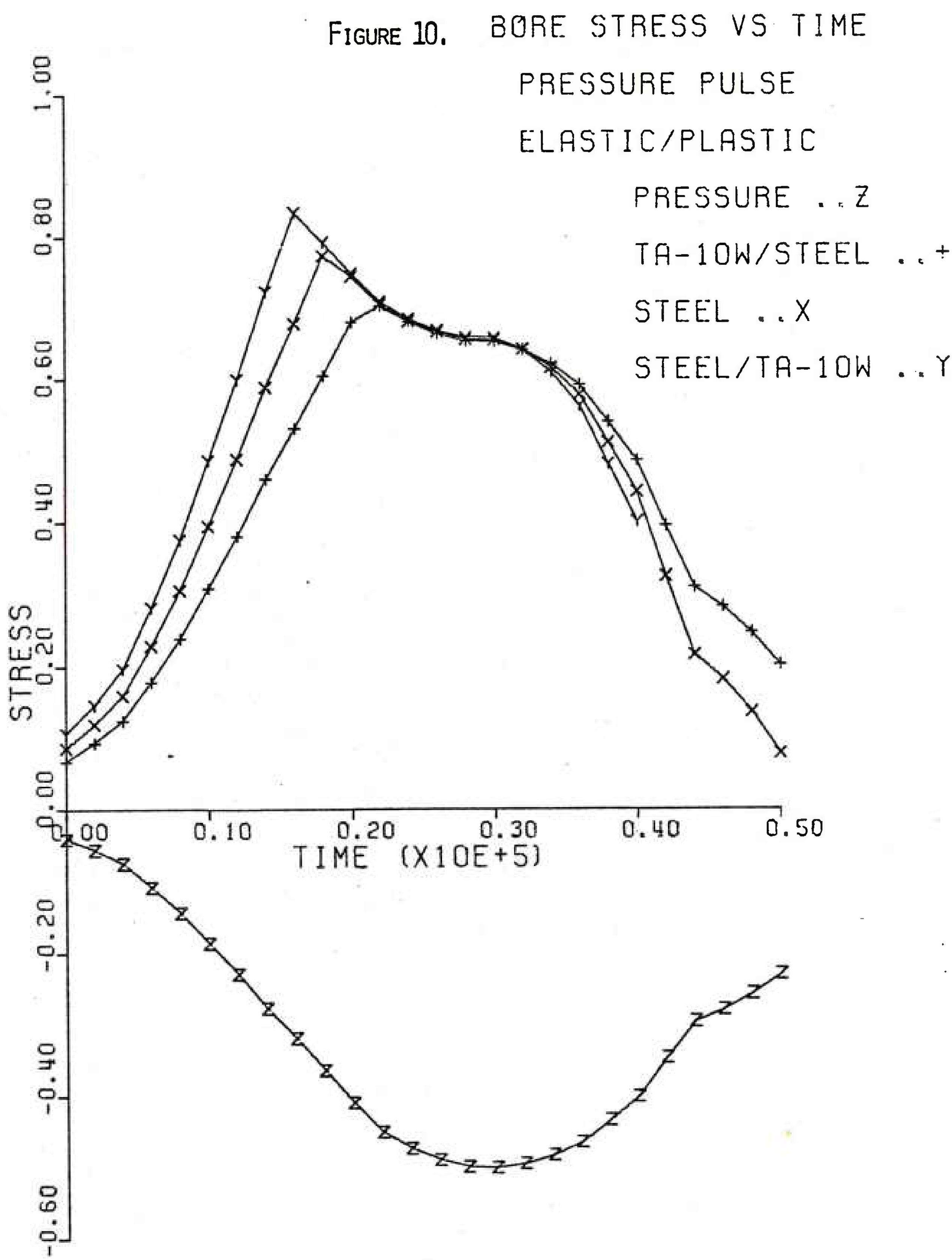
FIGURE 10. BØRE STRESS VS TIME
PRESSURE PULSE
ELASTIC/PLASTIC
PRESSURE ..Z
TA-10W/STEEL ..+
STEEL ..X
STEEL/TA-10W ..Y
STRESS
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
0.00
0.10
0.20
0.30
0.40
0.50
TIME (X10E+5)

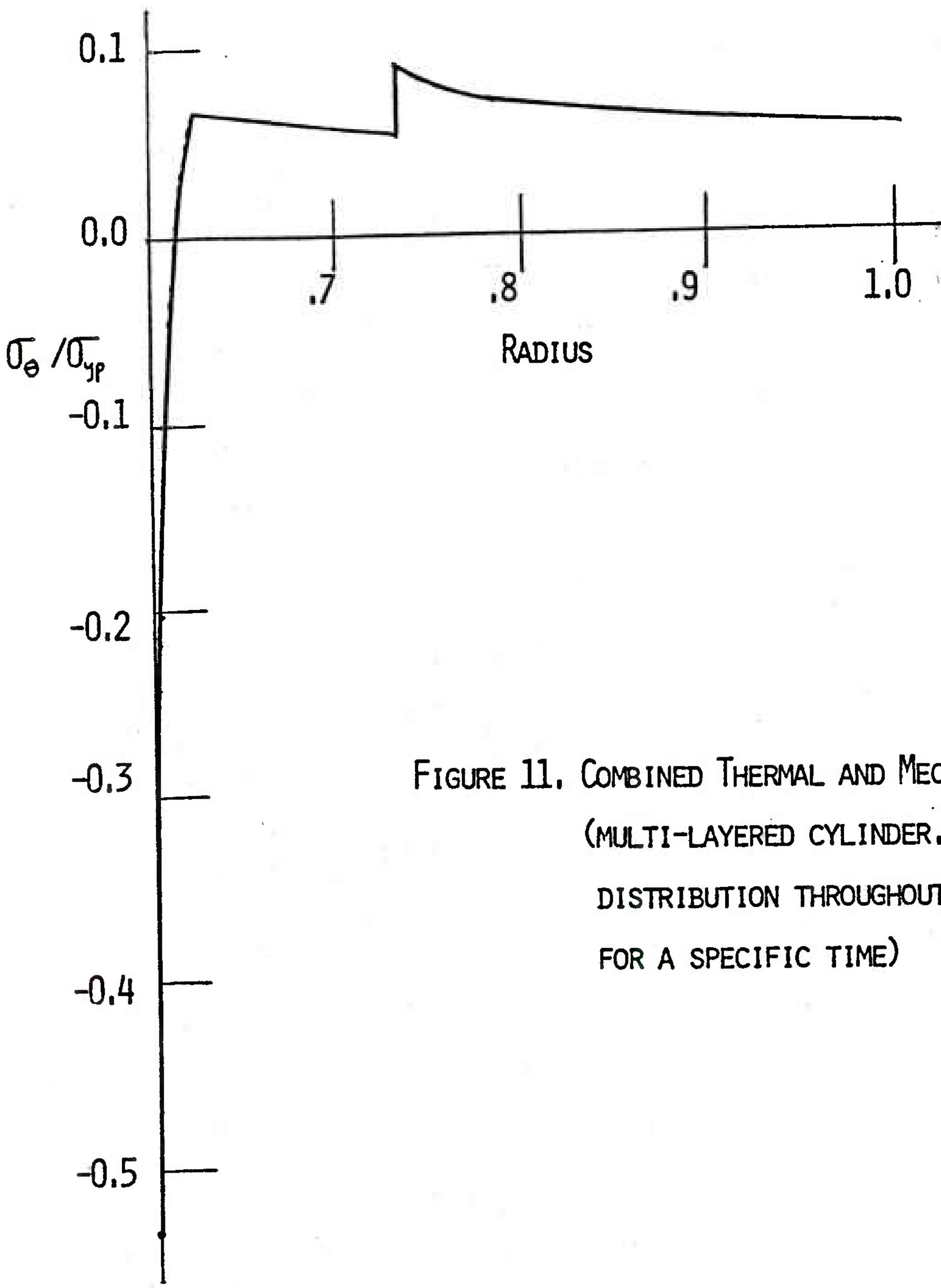

FIGURE 11. COMBINED THERMAL AND MECHANICAL LOADS
(MULTI-LAYERED CYLINDER, STRESS DISTRIBUTION THROUGHOUT THE WALL FOR A SPECIFIC TIME)

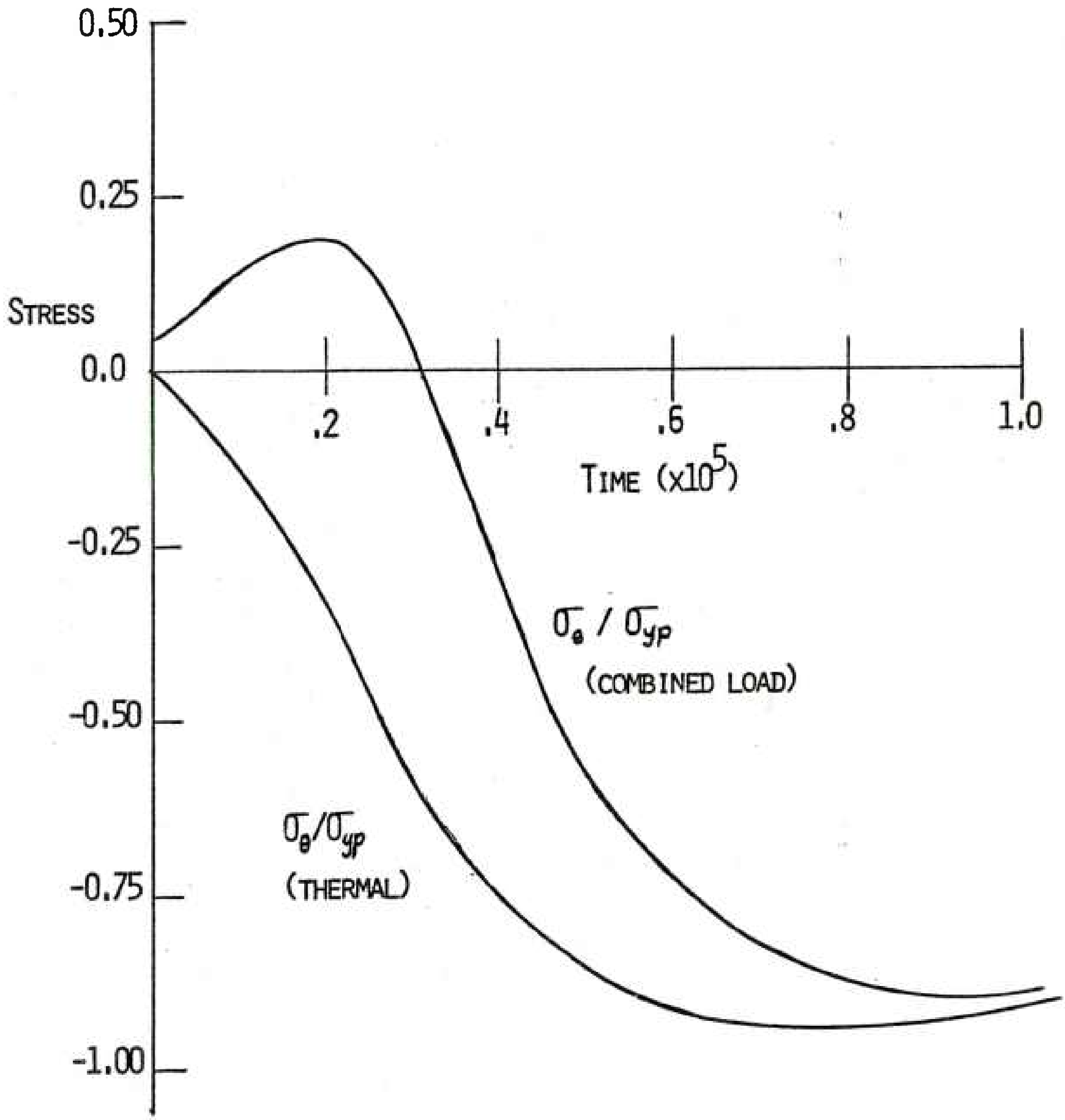

FIGURE 12. BORE STRESS VS TIME. ELASTIC RESPONSE. COMBINED THERMAL AND MECHANICAL LOADS MULTI-LAYERED CYLINDER. STEEL/TA-10W

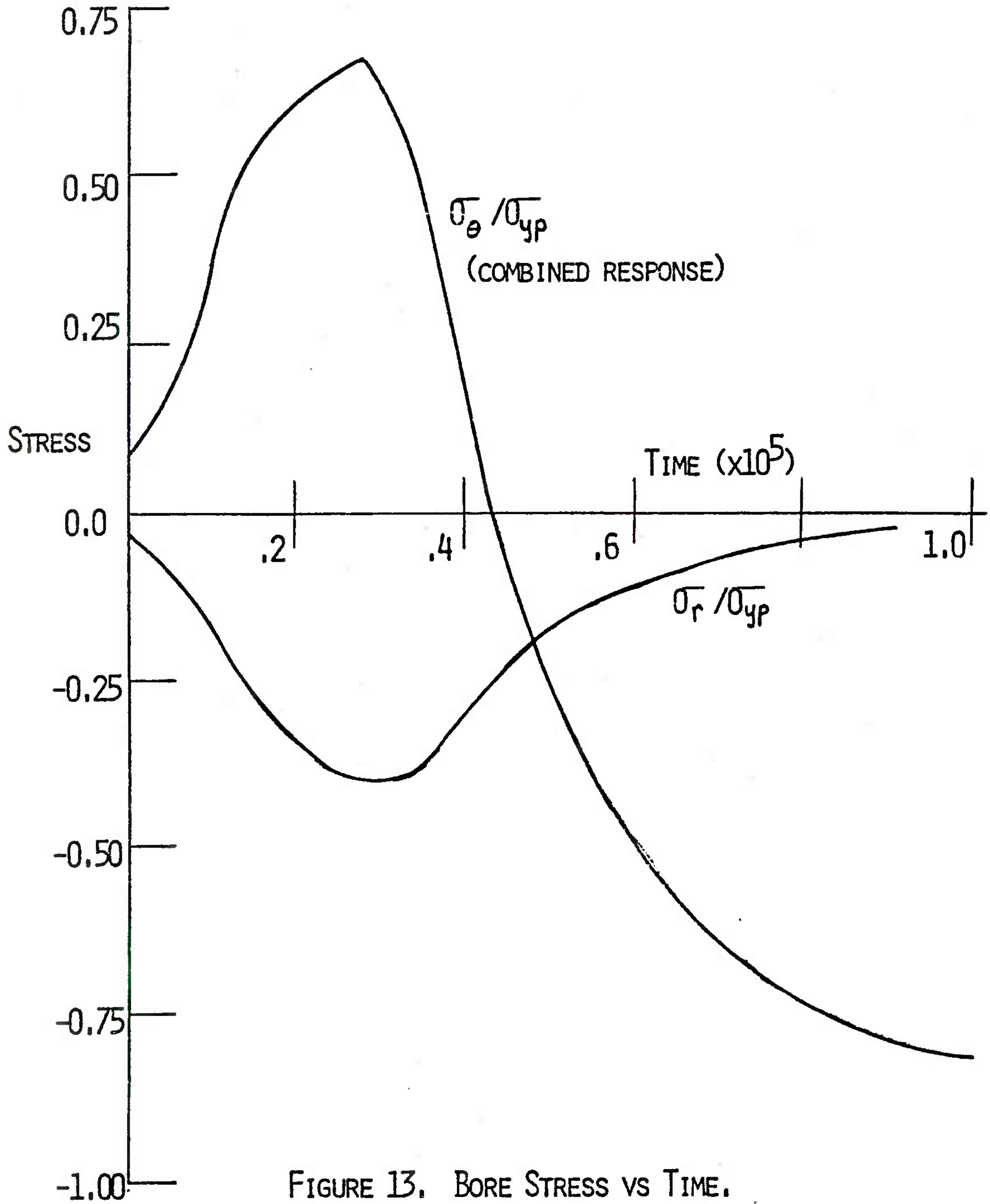

FIGURE 13. BORE STRESS VS TIME.
ELASTIC-PLASTIC RESPONSE. STEEL/TA-10W.
COMBINED THERMAL AND MECHANICAL LOADS.

REFERENCES

1. Vasilakis, J. D., "Temperatures and Stresses Due to Quenching of Hollow Cylinders," Transactions of the Twenty-Fourth Conference of Army Mathematicians, ARO Report 79-1.
2. Vasilakis, J. D. and Chen, P. C. T., "Thermo-Elastic-Plastic Stresses in Hollow Cylinders Due To Quenching," Transactions of the Twenty-Fifth Conference of Army Mathematicians, ARO Report 80-1.
3. Kovacs, J. E., "Computer Methodology For Large Caliber Artillery Cannon Heating and Cooling," Technical Report ARSED-TR-80001, December 1980.
4. Yamada, Y., Yoshimura, N., and Sakuri, T., "Plastic Stress-Strain Matrix and Its Application For the Solution of Elastic-Plastic Problems by the Finite Element," International Journal of Mechanical Sciences, 1968, V 10, pp. 343-354.

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MECHANICAL PROPERTIES DATA CTR BATTELLE COLUMBUS LAB 505 KING AVE COLUMBUS, OHIO 43201	1
MATERIEL SYSTEMS ANALYSIS ACTV ATTN: DRXSY-MP ABERDEEN PROVING GROUND MARYLAND 21005	1

NOTE: PLEASE NOTIFY COMMANDER, ARRADCOM, ATTN: BENET WEAPONS LABORATORY, DRDAR-LCB-TL, WATERVLIET ARSENAL, WATERVLIET, N.Y. 12189, OF ANY REQUIRED CHANGES.